A 1-bit High-Gain Flexible Metasurface Reflectarray for Terahertz Application

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***Abstract*—In this paper, a 1-bit, high gain and wide-band reflectarray metasurface is proposed. The proposed reflectarray operates from 0.9 THz to 1.4 THz giving operational bandwidth of 0.5 THz. The realized gain achieved is 32 dB at 1.4 THz while the maximum simulated aperture efficiency is calculated to be 55%. The reflectarray is designed on polyimide substrate with permittivity of 3.48 and loss tangent of 0.03 at THz frequencies. The dimension of the metasurface is 3×3 mm^2 and contains 3904 patch elements illuminated by a THz horn antenna. With high gain and flexible nature of the polyimide, the proposed metasurface is also suitable for wearable application.**

***Index Terms*—Metasurface, Terahertz, flexible, Reflectarray**

I. Introduction

In 2017 IEEE 802.15.3d standard [1] was approved as 100 Gbps wireless switched point-to-point system. Continuous data transfer, theoretically unlimited bandwidth and ultra-fast download are key features of the THz technology. It is expected to alter the telecommunications landscape. The THz band which spans from 0.1–10 THz has been finding its applications in numerous fields including post 5G communication network [2], imaging and detection, [3] and non-contact sensing of materials [4].

THz waves have a much higher frequency than millimetre waves, thus they are ultra-broadband. This translates to the data rate of the order of Terabits/sec. The disadvantage of having higher frequency is lesser propagation distance. Consequently, THz sources would require powerful antennas with a much higher gain to maintain better coverage. In present millimetre wave (mmWave) systems, the transmitting antennas are usually in the form of parabolic reflector antennas with bigger apertures to provide high gain. These apertures are illuminated by a horn antenna which works as a source or primary feed antenna.

An alternative to the parabolic antenna is the reflectarray antenna. These antennas have the advantage of being planar in geometry and are easier to fabricate due to flat profile. The reflectarray can be fabricated on any conventional PCB at mmWave frequencies. The reflectarray combines the benefit of both parabolic reflector and phased array technology. The horn antenna generates a spherical radiation pattern placed in proximity to the aperture. The patches are designed to provide phase delays to the incoming signals to collimate the reflected beam from its surface. Due to the higher frequency of THz, a conventional metal such as copper becomes lossy as the conductivity of copper decreases at THz. Therefore, it is usually replaced by Gold at THz. Similarly, dielectric substrates used at RF and mmWave frequencies are also replaced by materials with low loss tangent at THz [5].

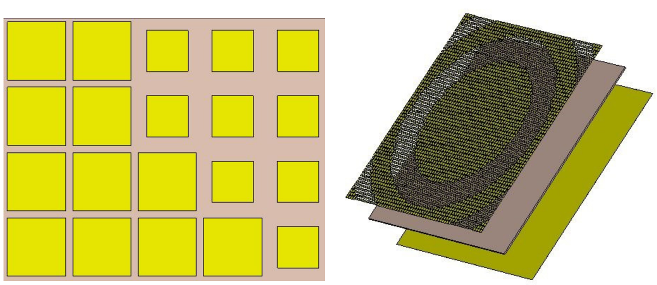
The first use of reflectarray in the THz range was demonstrated in [6]. The authors experimentally demonstrated the feasibility of square patches as reflectarray elements. In [7] a 360×360 reflectarray metasurface consisting of gold patches on a polydimethylsiloxane (PDMS) substrate was presented. Similarly in [8] a 416×416 reflectarray was demonstrated to work at 1 THz using gold patches supported by cyclic olefin copolymer (COC) dielectric substrate. A Graphene-based THz reflectarray was investigated in [9] at 1 THz. This Graphene reflectarray employs a quartz dielectric and consists of 25448 elements offering a gain of 28 dB at the centre frequency. With the introduction of Graphene at THz, tunable Graphene reflectarray has also been proposed in [10]. The authors have shown that by varying the conductivity of Graphene through external bias voltage effectively controls the phase response of the reflective elements.

Analog Control of a THz reflectarray with hundred of patches is tedious and challenging task. It requires every element to be controlled via different DC bias voltage and hence develop complex circuitry for each patch element. Instead of analog tuning, digital tuning can be applied with a discrete set of phases. In this regard, the concept of coded and programmable

metasurfaces has been proposed in [11]. Instead of employing continuous tuning, the unit cells are designed to maintain a discrete set of phases. A simple configuration is a 1-bit configuration that would require a phase of either 0° or 180° on the unit cell. It is worth mentioning that phase profile of the patches in the reflectarray is not affected by the absolute phase. A phase difference between the elements is to be maintained over the operating bandwidth of the reflectarray.
In this paper, we propose a 1-bit coded reflectarray metasurface with high gain and wide operating bandwidth. It is achieved by carefully selecting the size of the unit cell which maintains a 180° phase shift over a wide frequency band. The substrate height is optimized to maintain this phase profile across the whole bandwidth.

II. Unit Cell design

The proposed reflectarray is simulated and analyzed using a full-wave commercial electromagnetics solver, CST Microwave Studio (MWS) 2019. The top surface consists of gold patches etched on a flexible polyimide dielectric having a permittivity of 3.48 and loss tangent of 0.03. Bottom surface of the substrate has a gold ground plane. Thickness of the gold conductor is kept at 200 nm. The height of the polyimide has a significant effect on the reflectarray bandwidth. Its optimised value is found to be 20 um. This arrangement offers a good level of ease of fabrication as polyimide can be easily spin-coated on top of gold. The layout of the reflectarray can be seen in Figure 1.



(a) Gold patches on polyimide (b) Reflectarray structure

Fig. 1: Reflectarray structure and design

The periodicity of the unit cell is kept 50 um which is quarter-wavelength at the lowest operating frequency of the reflectarray metasurface, i.e., 0.9 THz. This sub-wavelength inter-element spacing makes the reflectarray act as a metasurface. The reflectarray metasurface given in Figure 2 consist of 61×61 elements. This specific reflectarray dimension is kept for practical consideration with currently available THz horn antenna provided by some companies.

III. Parametric Study

An investigation into the phase profile of the unit cell patch element was carried out in CST MWS. Before the complete simulation of reflectarray, unit cell with periodic boundary conditions was analyzed. In the design process, firstly, a

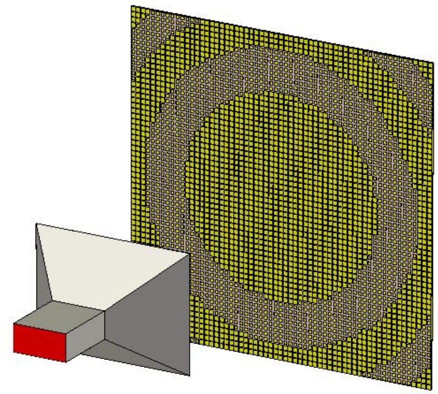


Fig. 2: Layout of the reflectarray metasurface illuminated by THz horn antenna

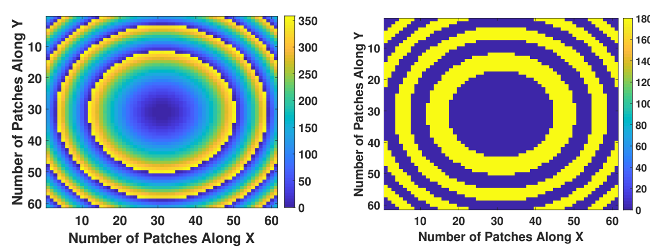
MATLAB code was written to generate the phase distribution function on the reflectarray metasurface. Secondly, from CST MWS studio, the dimension vs phase data was exported to MATLAB. The patch dimension is carefully selected and optimized to work at the specified THz frequencies. The phase distribution profile in the MATLAB was calculated as follows:

$$\Delta\varphi_{mn} = k\sqrt{Z^2 + (mD_x)^2 + (nD_y)^2} - (Z^2) \quad (1)$$

$$\phi_p = -k(mD_x\ Sin\theta\ Cos\varphi + nD_y\ Sin\theta\ Sin\varphi) \quad (2)$$

$$\phi_T = \Delta\varphi_{mn} + \ \phi_p \quad (3)$$

Equation 1 shows phase compensation of each element with respect to horn antenna position. Equation 2 is used to steer the beam in the desired direction. The plot for the ideal phase profile was computed using Equation 3, is shown in Figure 3a. This was finally converted to a 1-bit phase of 0° and 180° using Equation 4 seen in Figure 3b. The 1-bit phase profile is generated for beam steered towards 0 in both azimuth and elevation.



(a) (b)

Fig. 3: Phase distribution of reflectarray antenna: a) Continuous Phase distribution and b) 1-bit phase distribution

$$\phi_t|_{1-bit} = \begin{cases} 0, 0 < \phi_T < \pi \\ \pi, \pi < \phi_T < 2\pi \end{cases} \quad (4)$$

In conventional reflectarray design variation in patch size generates different phases on the reflective element. Once the optimised dimensions are obtained, it is mapped to the ideal

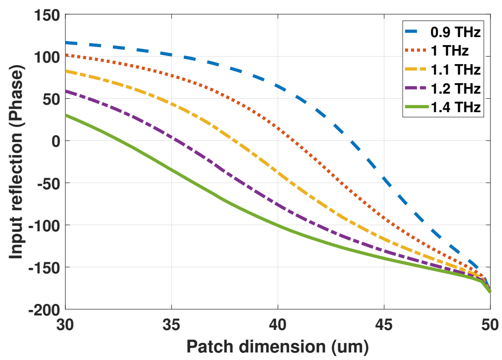


Fig. 4: Variation of phase profile with changing patch length

phase profile to make a reflectarray surface. To target wider operating bandwidth, the patch dimension must be able to generate a steady 360° phase on its surface to compensate the phase of the incoming beam. The simulated phase vs dimension profile for the proposed reflectarray metasurface is given in Figure 4. With the increase in patch size the patch shifts from being inductive to capacitive. It can be seen that using a simple square patch design, it is not possible to cover the entire 360° cycle. For this purpose, we have opted a simple technique to use a 1-bit coding scheme that would require only two patch dimensions to create a phase difference of 180°. This would, however, be at a cost of reduced gain.

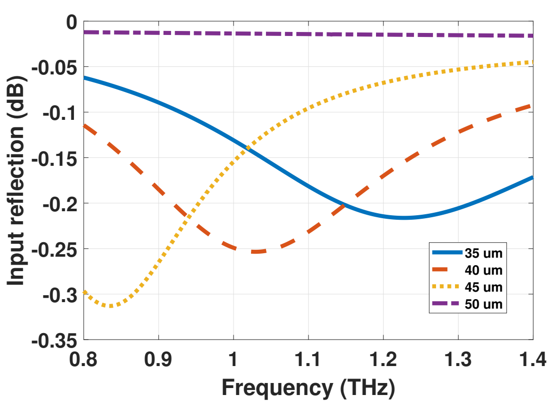


Fig. 5: Variation in reflection amplitude over the operating bandwidth

In Figure 5 and Figure 6 the amplitude and phase response of the unit cell in response to varying length of the patch is shown. It can be seen that over the entire bandwidth the reflection amplitude from the patch is almost 97%. In order to obtain a wider operating bandwidth for the reflectarray metasurface, the phase curve has been optimized to maintain a steady gradient. A 1-bit amplitude response is illustrated in Figure 7. Patch with the size of 31.6 um and 44.6 um have specifically been selected for 1-bit coding scheme. With these patch dimensions, a phase difference of 180°±20° in the entire operating bandwidth is obtained as depicted in Figure 8. It is observed that at the centre frequency of 1.1 THz the phase difference is exactly 180°. Around the centre frequency, the

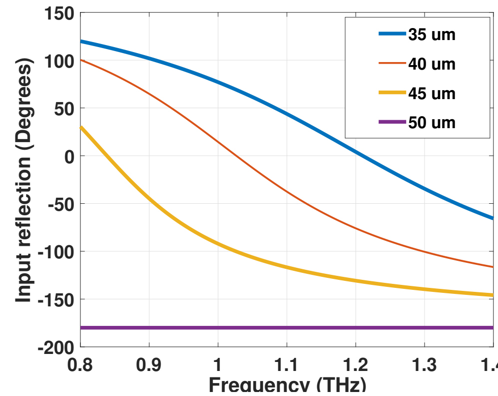


Fig. 6: Variation in reflection phase over the operating bandwidth

difference tends to decrease due the change in electrical length of the patch.

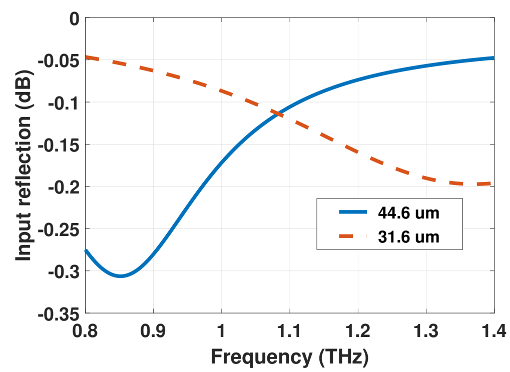


Fig. 7: Reflection amplitude for 1-bit scheme

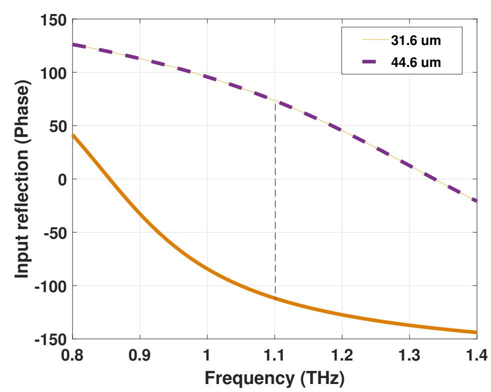


Fig. 8: Reflection phase for 1-bit scheme

IV. Results and Discussion

The simulated input reflection of the reflectarray metasurface is shown in Figure 9. In the simulation, the horn antenna is excited to illuminate the reflectarray metasurface. The input reflection is showing good impedance matching from 0.9-1.4 THz giving a bandwidth of 0.5 THz.

Apart from impedance bandwidth, it is also important to analyze the radiation pattern from the reflected metasurface. The E-plane radiation pattern for three different frequencies is given in Figure 10. It can be seen that that radiation is focused in the broadside direction with 4°of 3-dB beamwidth. Due to a large number of elements, the reflectarray metasurface has a very sharp and focused beam. The calculated side-lobe level is high in all the frequencies. This is due to the phase quantization applied in the phase profile.

The realized gain of the reflectarray metasurface is given in Table I. At the lowest operating frequency of 0.9 THz, the realized gain is minimum, i.e., 22 dB. This could easily be explained since the phase difference is the lowest at this point. The realized gain is highest at 1.4 THz. Apart from the decreasing phase difference at the highest operating frequency, the physical aperture becomes electrically large giving higher gain.

TABLE I: Simulated gain of the 1-bit THz reflectarray metasurface

Frequency (THz)	**0.9**	**1.15**	**1.4**
Gain (dB)	22	30	32

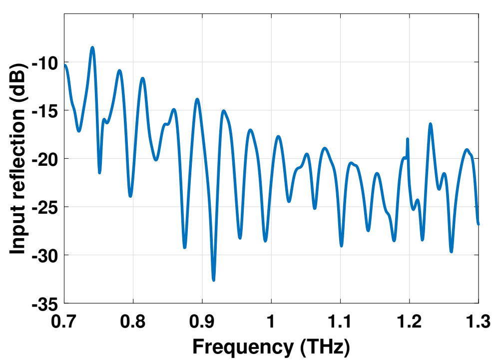


Fig. 9: Simulated input reflection of the 1-bit THz reflectarray metasurface

V. Conclusion

A high gain and wide-band THz reflectarray metasurface has been designed and simulated. Instead of using a continuous phase gradient over the reflectarray surface, a 1-bit coded phase profile is adopted. In this coding scheme, a 180° phase difference is maintained among the desired patches. With Graphene as a tuning element, this would require only two sets of bias voltages to control the beam. This is left as future work of this paper. The maximum realized gain achieved by the reflectarray metasurface is around 32 dB at 1.4 THz. The total bandwidth of the proposed 1-bit coded reflectarray is 0.5 THz at the centre frequency of 1.15 THz. Due to the flexible nature of of the dielectric substrate, the proposed reflectarray is also ideal for wearable application.

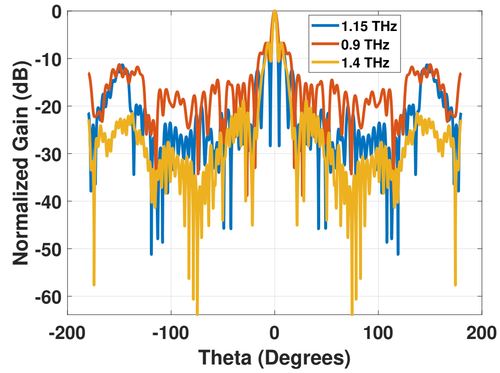


Fig. 10: Normalized gain of the reflectarray metasurface

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